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Factors affecting surface and release properties of thin Polydimethylsiloxane films

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Abstract

Polydimethylsiloxane (PDMS) elastomers are commonly used as dielectric electroactive polymers (DEAP). DEAP films are used in making actuators, generators and sensors. In the large scale manufacture of DEAP films, release of films from the substrate (carrier web) induces some defects and pre-strain in the films which affect the overall performance of the films. The current research is directed towards investigating factors affecting the peel force and release of thin, corrugated polydimethylsiloxane films used in DEAP films. It has been shown that doping the PDMS films with small quantities of perfluoroether allylamide (PFE) lowered the surface energy which could ease the release. This is further investigated together with an evaluation of the resulting change in actuator performance. The relationship between the adhesive energy, surface energy, Young's modulus and peel force of the films is analyzed.

Keywords: carrier web, DEAP, elastomers, PDMS, release, surface energy

1. Introduction

In the large scale manufacture of DEAP films, the PDMS elastomer mixture is applied to the substrate (carrier web) and then peeled off the substrate after the elastomer has cured completely. [1] The process of release from the substrate is not as smooth as it is desired, and induces considerable pre-strain and defects in the film which affects the performance of the films as actuators. To ease the process of release, release agents in the form of sprays or liquids cannot always be used. Modifying or replacing the web for the processing of the micro-structured films is not an option right now due to the commercial unavailability of such products in large quantities for the continuous process of producing micro-corrugated DEAP films.

The surface energy of PDMS is $19\sim 21\text{ mJ/m}^2$ [2] which explains its inert nature towards many chemical species and poor adhesion to many substrates. By addition of suitable surface active block copolymers it has been shown that the surface energy can be decreased further or make the film selectively non-adhesive to a particular substrate.[3] A polymeric additive of lower surface energy than its host matrix is known to adsorb preferentially at the free surface and consequently decreases the adhesion of that surface towards a particular substrate.[3] The substrate on which the PDMS films are made is a polyethylene terephthalate (PETE) coated with microscale corrugations of methylacrylate. This is the substrate used in the large scale industrial manufacture of DEAP films.[1]

Surface tension, Peeling and Release

The molecules sitting on a free surface of the film will have lesser binding energy than those molecules in the bulk. This missing (negative) binding energy can be viewed as a positive energy added to the free surface. External forces must perform positive work against internal surface forces to increase the area of a surface. These internal surface forces are called surface tension defined as the normal force per unit area. [4] Surface tension is present in all surfaces and interfaces. The surface energy density associated with an interface of solid or liquid against a gas is always positive because of the missing negative binding energy of surface molecules. Interfaces between solids and liquids or between solids and solids are not required to have positive interfacial energy density. The sign depends on the strength of the cohesive forces holding molecules of a material together compared to the strength of the adhesive forces between the opposing molecules of the interfacing materials. If the interfacial energy between two liquids is negative, then large amount of energy can be released by mixing them and hence the liquids get mixed instead of staying separate. Immiscible liquids like oil and water have a positive interfacial energy density, which makes them seek minimum interfacial area. [4]

The peel force required to peel a film from a substrate is a complex function of geometry, the mechanical properties of the film and the substrate, thickness of the film, interfacial cohesive properties and also the friction between the surfaces. A detailed study and analysis of the peel test and the factors which govern the peel force has been presented by Thouless et al. [5]

There are many theories to determine the peel force, [5,6] adhesive fracture energy or the interfacial adhesion [7] when a film is being peeled from a substrate. Thin-film peeling theory by Kendall [8]

which explains the peeling of a thin elastomer film from a rigid substrate will be used to analyze the peeling in this context.

Consider an elastomer film of thickness d which is being peeled from a rigid substrate at a peel angle θ with a force F (Figure1). The elastomer has a Young's modulus E . The adhesive energy between the film and the glass substrate is R . Consider a unit length Δc of the film being peeled from the substrate between the points A and B. [8] The width of the film at any given point is b . The three contributions to the energy changes involved in the peeling process are

- 1) Surface energy - due to creation of new surfaces $[-bR\Delta c]$
- 2) Potential energy- due to the movement of the applied force $[F(1-\cos\theta)]$
- 3) Elastic energy -due to extension of the film in the direction of the applied force $\left[\frac{F^2\Delta c}{2bdE}\right]$

Adding up these contributions and assuming energy conservation the following equation is obtained. [8]

$$-bR\Delta c + F(1 - \cos\theta)\Delta c + \frac{F^2\Delta c}{2bdE} = 0 \quad (1)$$

In our case, the corrugations on the surface of the carrier web make the release process all the more difficult as it increases the surface area and hence larger force is needed to peel the film.

From the equation (1) the adhesive energy R can be calculated. R is different from surface energy, work of adhesion or any thermodynamic quantity and R gives an estimate of the adhesive force between the substrate and the film. If the R between the substrate and the elastomeric film is high, then the force F required to peel the film will also be high. The smaller the peel angle, the smaller will be the potential energy contribution. Since, the standard peel tests are performed at $\theta = \pi/2$ or $= \pi$, the peel angle will not be modified. The elastomeric contribution to peel is governed by the E , which is a material property. The surface energy contribution to peel force can be lowered, if the surface energy can be brought down. This should preferably be done without affecting the bulk properties of the material (mechanical and dielectric) properties.

To bring down the surface energy of the PDMS, it will be modified with small quantities of a perfluoroether additive that contains low-energy trifluoromethyl (CF_3) groups. [9] These low-energy CF_3 groups will migrate to the two surfaces of the silicone film and will segregate. Because of the high density of the CF_3 groups in the perfluoroether it is possible to obtain a silicone surface

with very low surface energy just by adding very small quantities of perfluoroether. Perfluoroether allylamide $[F(CFCF_3CF_2O)_7CFCF_3CONHCH_2CH=CH_2]$, PFE] added to addition curing PDMS (0.3-1.5 weight %) lowered its surface energy from 19 to 8 mJ/m² .[9] The PFE molecules added to the PDMS are chemically bonded to the silicone network by the platinum catalyzed hydrosilation reaction.[9] The PDMS films are doped with 1% PFE (i.e., 1% of the mass of PDMS) and the films were examined to see if they yield favorable results.

To investigate the influence of the PFE on the mechanical properties, the linear rheological properties of the pure PDMS and PDMS doped with PFE will be examined. Furthermore, to investigate the changes induced on the surface of the films by the PFE, contact angle measurements and peel tests on these surfaces have been performed. Dielectric permittivity tests are also conducted to investigate the influence of PFE on permittivity as an increase in the dielectric permittivity would be an extra advantage to the DEAP films and hence not solve a process related problem only. [10]

The allyl groups ($-CH=CH_2$) of PFE react with the hydride groups ($-Si-H$) of the crosslinker (methyl hydrogen siloxane) and compete with PDMS in the hydrosilation reaction. To ensure proper bonding of the PFE to the silicone network and complete crosslinking of PDMS, sufficient crosslinker has to be added to the reaction mixture. The effects of the additional crosslinker and platinum catalyst in the reaction mixture are also investigated. Hence, various compositions of crosslinker and catalyst are used in the reaction mixture.

2. Experimental

2.1. Materials

The PDMS elastomer, oil and inhibitor used for the following set of experiments are 1) Elastosil RT-625 (a commercially available RTV silicone), 2) Powersil Fluid TR50 and 3) Inhibitor PT 88 respectively, obtained from Wacker Chemie AG, Germany. The PFE (KDP-4645) was supplied by DuPont Krytox Performance Lubricants, USA.

2.1.1. Carrier web

The carrier webs on which the release property of PDMS film will be tested is made of temperature stabilized polyethylene terephthalate band (0.2mm) coated with methyl acrylate UV resin. The surface of the carrier web has micro-scale corrugations (Figure 2). There are two types of carrier

webs used at Danfoss PolyPower A/S (Nordborg, DK) depending on whether the corrugation lines are along the length of the web (down-web) or perpendicular to the length of the web (cross-web). Also there are two types of carrier webs defined by the wave depth and period. One that has a depth of 5 μm and a period of 10 μm (30% web) and is capable of stretching to about 35% strain and another where both the depth and period are 7 μm and this is capable of stretching up to about 80% strain (100% web). [1, 11] The carrier web has negligible strain under the present process conditions and the peel dynamics are not affected.

2.2. Instrumentation & Specifications

2.2.1. Rheological experiments

Rheological measurements (time sweep and frequency sweep) on the silicone networks were performed with a controlled stress rheometer AR-2000 (TA instruments, USA).

2.2.2. Contact angle

Contact angle experiments are performed using the Contact Angle system (OCA Data Physics, Germany). The probe liquids are water and hexadecane (product no.H0255) from Sigma-Aldrich.

2.2.3. Peel test

Peel tests were performed in Danfoss PolyPower A/S using the Zwick/Roell (Zmart.pro, Germany) material tester.

2.2.4. Dielectric permittivity

The dielectric permittivity tests on the samples are performed using Novocontrol Alpha-A (Novocontrol Technologies GmbH & Co. KG, Germany), a high performance frequency analyzer.

2.3. Procedure

2.3.1. Preparing the addition curing PDMS mixture and films

Elastosil RT-625 is supplied as premixes A and B. Premix A is a mixture of vinyl terminated PDMS and crosslinker while Premix B is a mixture of vinyl terminated PDMS and catalyst amongst other components such as fillers. Premix A and premix B are mixed in the prescribed proportions (9:1), using the speed mixer DAC 150FVZ-K (Synergy Devices Ltd., UK) for 2 minutes at 1000 rpm. Similarly, samples with Elastosil RT-625 (9:1), PFE 1% (of the mass of Elastosil RT-625), oil

15% (of the mass of Elastosil RT-625) and inhibitor 0.8% (of the mass of Elastosil RT-625) are also mixed.

Another set of samples are made with Elastosil RT-625 where A and B are mixed in the ratio 10:1, so that the resulting mixture has more crosslinker. The amount of PFE added to this mixture is also 1w/w %. The crosslinker percentage is increased in the second set of samples so that the PFE has sufficient crosslinker to react with. Oil (15%) and inhibitor (0.8%) are also added to some elastomer samples of this set to investigate the influence of these constituents as well.

To examine the effects of additional catalyst, next set of samples are made, where Elastosil RT-625 A and B are mixed in the ratio 9:1.1. PFE (1%), Oil (15%) and inhibitor (0.8%) are also added to this set of samples.

Mixing the premixes A and B of Elastosil RT-625 will result in the hydrosilation reaction of the vinyl terminated polydimethylsiloxane ($-\text{CH}=\text{CH}_2$) with the hydride cross linker ($-\text{Si}-\text{H}$) in the presence of the platinum catalyst, resulting in a PDMS network. PFE also reacts with the cross linker, when present in the mixture (Figure 3). In total 18 samples are made with varying compositions (Table 1), to investigate the effects of PFE, additional cross linker and oil on the silicone films. The segregation of PFE in the surface is the same in the film-air interface and the film-substrate interface. The PFE migrates to the surfaces/interfaces of the PDMS film uniformly. FTIR curves showing the peaks with same intensity for PFE on both the interfaces of the PDMS film have been presented in the supporting information.

2.3.2. Rheological tests

To investigate the effects of PFE, additional crosslinker and catalyst on the mechanical properties of Elastosil RT-625, rheological tests are performed.

Time sweep

Time sweeps of 18 samples (Table 1) are performed at 2% strain, at temperatures 23°C and 80°C and in a frequency of 1 Hz. The applied strain (2%) is ensured to be within the linear regime of the material. Samples with inhibitor are cured at 80°C, as the inhibitor inhibits the curing at room temperature. Samples without the inhibitor are cured at 23°C.

Frequency sweep

Mechanical characterization (frequency sweeps) of the 18 samples is performed by LVE measurements. Films of thickness 1mm (1000 microns) are prepared with the 18 sample mixtures. After complete curing, the films are cut to make 25mm diameter discs. LVE measurements on these samples are performed from a frequency of 100 Hz to 0.001 Hz with 2% strain (which is ensured to be within the linear regime of the material based on an initial strain sweep) using the 25mm aluminum parallel plate geometry at 25°C. The normal force applied by the aluminum disc on the sample is 5-10 N.

2.3.3. Contact angle tests

As described above, addition curing mixtures are prepared with the 18 different compositions. Films of thickness 1mm are made on a flat substrate. Once fully cured, the films are tested for contact angles.

Advancing and receding contact angle experiments are performed on the 18 samples using water as the probe liquid. Static contact angle measurements are made with hexadecane as the probe liquid. Since hexadecane swells the surface of the PDMS films, the contact angle measurements are made within 5~10 seconds of the drop coming into contact of the film.

2.3.4. Peel tests

Peel tests are performed on the 18 samples to estimate the peel force and the adhesive force. Films of thickness 100 μm are made on the 30% down web with the addition curing mixtures using a 3540 bird film applicator (Elcometer, Germany). The dimensions of the samples are 30×30 mm. Once the films are fully cured on the carrier web, they are tested for peel force with a peel angle of 90°. A peel curve is obtained from plotting the peel force versus length of sample peeled.

2.3.5. Dielectric permittivity

For the permittivity tests also films of thickness 1mm are made from the 18 addition curing mixtures and once fully cured, discs of diameter 25mm are cut of it. They are then tested for their dielectric permittivity.

3. Results and discussions

3.1. Rheological tests

3.1.1. Time sweeps

The time sweeps of sample 6 and sample 12 are shown in Figure 4, which, are the samples showing the most deviation due to highest (1%) and lowest (0%) amounts of PFE, respectively. After the onset of the hydrosilation reaction, the PDMS network approaches chemical gelation. A cross-linking polymeric system is said to reach its gel point (GP) at a critical extent of the crosslinking reaction at which either the weight average molecular weight diverges to infinity (infinite sample size) or the first macromolecular cluster extends across the entire sample (finite sample size).[12,13] The GP which is at the cross-over between G' and G'' is an important processing parameter for DEAP materials, for more details see references. [10, 12, 13] The addition of PFE to the Elastosil RT-625 does not modify the GP significantly. From the results it can be concluded that the addition of 1 w/w% of PFE does not lead to any changes in the process conditions for the RTV rubber, which is very favorable.

3.1.2. Frequency sweeps

Frequency sweeps of samples 6 and 12 are compared in Figure 5 which again, are the samples showing most deviation due to 1% and 0% of PFE, respectively. From the frequency sweeps (Figure 5) it is evident that the storage modulus G' of pure Elastosil RT-625 film is not influenced much by the addition of PFE. The addition of PFE lowers the elastic-modulus by a few percent which is within the experimental uncertainty of the measurements, but the increase in G'' with the addition of PFE confirms that there is a small but still fairly insignificant decrease in the elasticity of the material with PFE. The deviation in G'' is much clearer since the magnitude of G'' is dominated by the very small sol fraction in contrast to G' which is dominated by the elastically active material. [14]

In Table 1, the elastic moduli of all the samples G' ($\omega \rightarrow 0$), as well as other process related properties such as the time for the material to obtain 97% of its final strength (t_{97}) and the cross over point of G' and G'' are tabulated. The t_{97} is also an important parameter for many processing considerations as it may be overly expensive to wait for the last 3% of reaction which proceeds very slowly and in the case of fairly stoichiometric networks doesn't influence the elasticity significantly.

3.2 Contact angle and Surface energy

3.2.1. Advancing and receding drop with water

The advancing and receding water contact angle experiments are performed on the 18 samples. The Elastosil RT-625 samples without PFE had on an average 110 as the water contact angle, which is characteristic of PDMS [2]. Samples with 1 w/w% PFE had on an average 115 as the water contact angle. Results/experimental data of contact angle tests have been presented in the supporting information.

3.2.2. Static contact angle with n-hexadecane

The static contact angles measured with n-hexadecane are tabulated in Table 1.

Fowkes' method to calculate the surface energy [15]

According to the Fowkes' method the surface energy of a solid surface (S) can be calculated using the contact angle of a liquid (L) using a simple formula.

$$\frac{\sigma_L(\cos\theta+1)}{2} = \sqrt{\sigma_S^P} \sqrt{\sigma_L^P} + \sqrt{\sigma_S^D} \sqrt{\sigma_L^D} \quad (2)$$

Where, $\sigma_L = \sigma_L^P + \sigma_L^D$, where, σ = is the surface energy (surface tension), P = denotes the polar component of surface tension, D = dispersive component of surface tension.

When we use a liquid whose polar component is zero, the surface tension of the liquid will then be $\sigma_L = \sigma_L^D$. Hence equation (2) will become

$$\sigma_S^D = \frac{\sigma_L(\cos\theta+1)^2}{4} \quad (3)$$

Thus, using the contact angles of a polar liquid like water and a non-polar liquid like n-hexadecane, one can estimate the surface energy of a solid using the equations (2) and (3). The results are tabulated in Table 1. The samples doped with PFE have a much lower surface energy than the pure Elastosil RT-625 samples (Figure 6).

Figure 6 shows a comparison of the surface energy with the contact angle of n-hexadecane. Films with PFE have a higher contact angle with n-hexadecane and a lower surface energy, compared to the films without PFE. Samples 12, 13, 14 and 17 (20.3, 19.4, 20.8, 18.9 mN/m respectively) have almost similar surface energy values, of which samples 14 and 17 have PFE and samples 12, 13 do not have PFE.

3.3. Peel tests

A peel curve obtained from the peel test of sample 3 is shown in Figure 7. The peel force F (N/mm), which is the force used in peeling a length of 1mm of the sample is plotted against the length of the sample that is being peeled. From the peel curve we see that F increases to a maximum value and then falls to a low constant value. From examining the F values of the samples, it is observed that samples 6 and 12 with 15% oil and 0.8% inhibitor have the maximum F values. Samples 5,8,10,11,15,17 and 18 all of which had 15% oil in its composition have low F values compared to the average of 0.0157 N/mm. On the contrary, samples 7, 9 and 16 which have inhibitor 0.8% (without oil) had higher F values than the average of 0.0157 N/mm. Presence of oil in the addition curing mixtures certainly makes the release easier, as it acts like a release agent. The values of maximum and constant peel force of all samples are tabulated in Table 1.

In the Figure 8 the surface energy and the F of the samples are plotted. It is seen that the samples with low surface energy and those with high surface energy both have similar patterns with F . The reduction of surface energy of the samples did not reduce or affect their F . Since the carrier web is very thick and rigid, the stretching of the web is never observed during the experiments.

3.3.2. Calculation of Adhesive force ' R '

Using the peel equation (4), the adhesive energy R is calculated. [8]

$$\left(\frac{F}{b}\right)^2 \frac{1}{2dE} + \left(\frac{F}{b}\right)(1 - \cos\theta) - R = 0 \quad (4)$$

$$E = 2G(1 + \nu)' \quad (5)$$

Where, G is the static shear modulus and ν is the poisson ratio.

The F is obtained from the peel tests and the E is calculated from the equation (5). The value of G ($G = G'(\omega \rightarrow 0)$) [16] is obtained from the frequency sweeps (Table 1) of the rheological tests and the poisson ratio (ν) for silicone elastomers (rubber) taken as 0.5. The maximum value of F is used for all calculations in order to estimate the maximum R between the film and the substrate during the processing. A comparison of samples 2 and 12 clearly shows that as the E increased, the R decreased. [Sample 2 has $F = 0.016\text{N/mm}$, $E = 0.18\text{MPa}$, and the calculated $R = 27\text{N/m}$. Sample 12 has $F = 0.022\text{N/mm}$, $E = 0.10\text{MPa}$ and the calculated $R = 61.7\text{N/m}$.]

From Figure 9 and 10 one can understand the relationship of the E , R and F . From Figure 9 it is observed that as the F increased the value of R also increased. To lower peel force, the adhesive energy needs to be lowered. From Figure 10, it is observed that R and E are related inversely, in accordance to equation (1). As the E of the samples increased, their R value decreased, thus making their release easier. Though surface energy, F and R at the interface are related through the action of

surface forces, the relation is not obvious. [17] The relationship of F , R , E and release can be understood further from the theory proposed by Johnson, K.L. et al. [17] Every surface has a surface energy resulting from the action of surface forces. When two surfaces are in intimate contact, these surface forces act as attractive (adhesive) forces. The strength of the attractive (adhesive) force between two surfaces depends on the contact surface area.[17] Interfacial gaps due to surface asperities or dust particles will strongly influence the adhesion between the surfaces because the attractive forces decrease rapidly with increasing separation.[17] Materials with low elastic modulus, will even out easily against a substrate and make very good contact. Therefore they are strongly adhered to the substrate. [17] Hence, to peel the film off, one needs to overcome the adhesive forces and apply a high F . To make the release easier, the contact at the interface needs to be reduced to prevent the surfaces from adhering strongly. That is what release agents like oils and surfactants do, namely reducing the good contact to ease the release of a surface from another surface. On the contrary, materials with high Young's modulus will not flatten out against another surface and cannot make an intimate contact, hence, less adhesive force.

3.4. Dielectric Permittivity

In Figure 11, dielectric permittivity ($\epsilon = \epsilon' + i\epsilon''$) of samples 1, 3, 5, 13, 14 and 15 are shown. The dielectric constant is an essential piece of information when designing capacitors or in our case an actuator which operates with the same principle of a capacitor.

The permittivity (ϵ) value of PDMS films used in our experiment is usually around 3.2 [10]. The tests conducted confirmed that the ϵ of the samples are not influenced much by PFE addition and were well within the allowed limits. The variation in ϵ was in a range of 3.1 to 3.4 (Figure 11). Also, the little variation in permittivity values can be attributed to the addition of oil and inhibitor.

4. Conclusions

PDMS was doped with 1% PFE to lower the surface energy and as expected that the surface energy was lowered. The addition of PFE to the Elastosil RT-625 did not influence the storage modulus G' much, as seen from the time sweeps. The dielectric permittivity of the samples was also not modified by the addition of PFE. Elastosil RT-625 doped with PFE has high contact angle in the advancing drop and during the receding drop the surface behaves more hydrophilic than the pure Elastosil RT-625 films. This can be due to the presence of high energy moieties near the surface.

The amide groups just beneath the surface are highly polar and hence get exposed when water (polar liquid) comes into contact with the surface. [9]

Though the surface energy reduced by the addition of PFE, the peel force values did not decrease. The reason for this is because the elastic contribution to the peel force is much higher than the potential and the surface energy contribution. For the investigated elastomer films, the Young's moduli are low, which makes them even out against surfaces easily and make good contact. This contact increases the adhesive forces, making the release hard. The samples with low Young's moduli have a higher adhesive energy between the film and the substrate than those with higher Young's modulus. So, tuning the elasticity of the networks is actually the easiest path for reducing the release problems of thin silicon films, when other solutions like using a release agent is not an option.

5. Acknowledgement

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Figure legend

Figure 1. Peeling an elastomer film from a rigid substrate [8]

Figure 2. The micro scale corrugations on the carrier web [1]

Figure 3. Modification of PDMS network with PFE (hydrosilation reaction) [9]

Figure 4. Curing profiles of sample 6(Elastosil (9:1.1) + oil (15%) + inhibitor (0.8%) + PFE (1%)) and sample 12(Elastosil (9:1.1) + oil (15%) + inhibitor (0.8%)) at 80°C

Figure 5. Frequency sweeps of sample 6 (Elastosil (9:1.1) + oil (15%) + inhibitor (0.8%) + PFE (1%)) and sample 12 (Elastosil (9:1.1) + oil (15%) + inhibitor (0.8%)) at 23°C

Figure 6. Surface energies calculated using Fowke's method

Figure 7. Typical peel curve

Figure 8. Comparison of the surface energies of the samples with peel force F

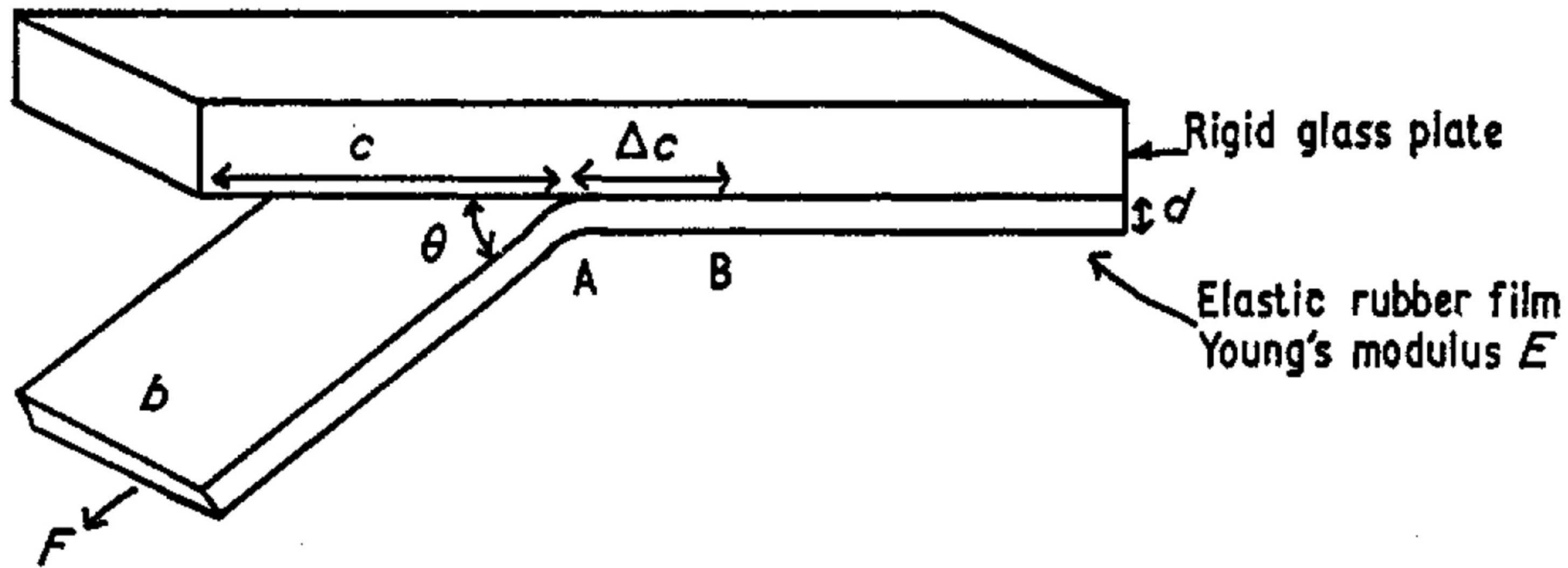
Figure 9. Relationship of the adhesive energy R and peel force F

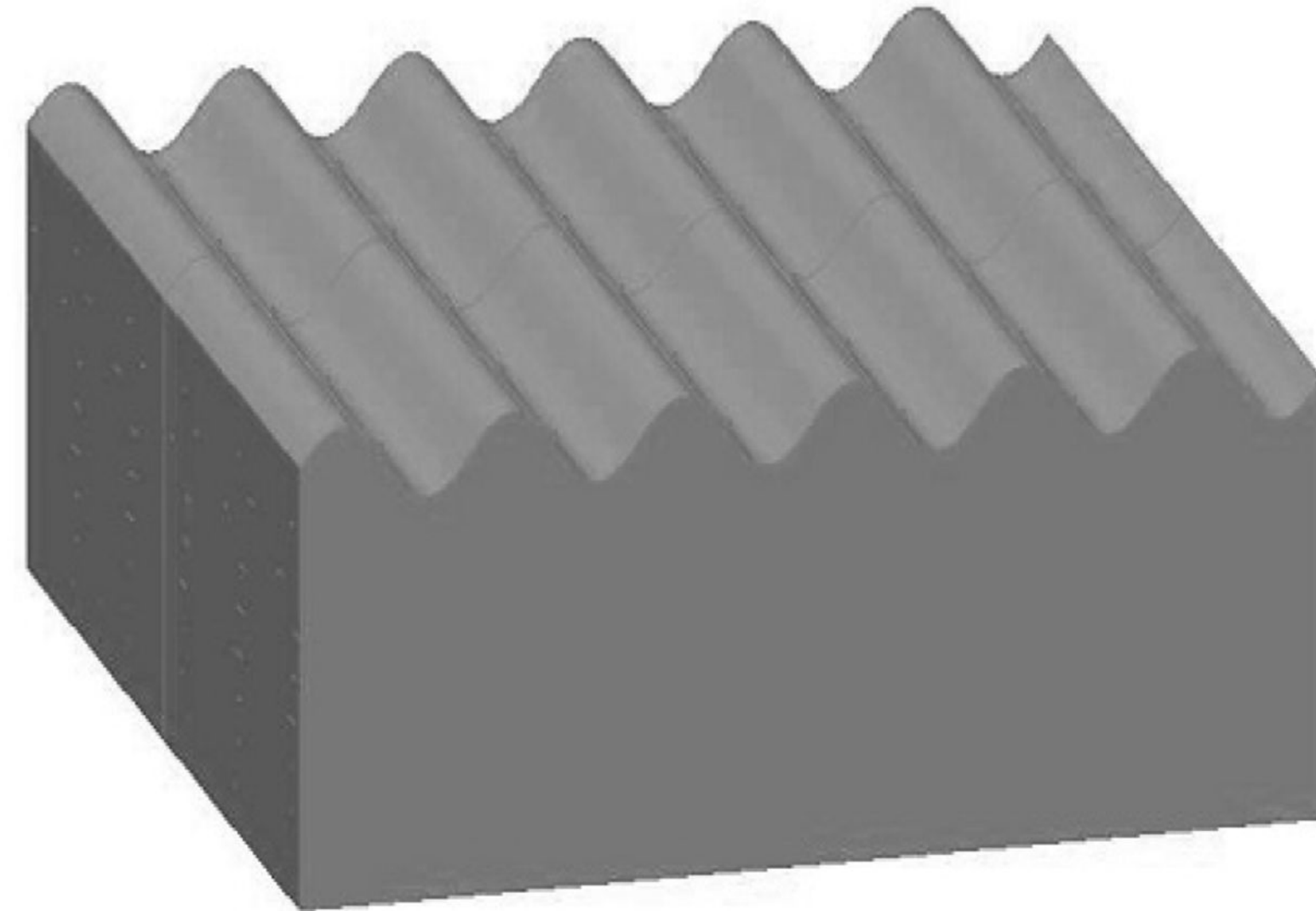
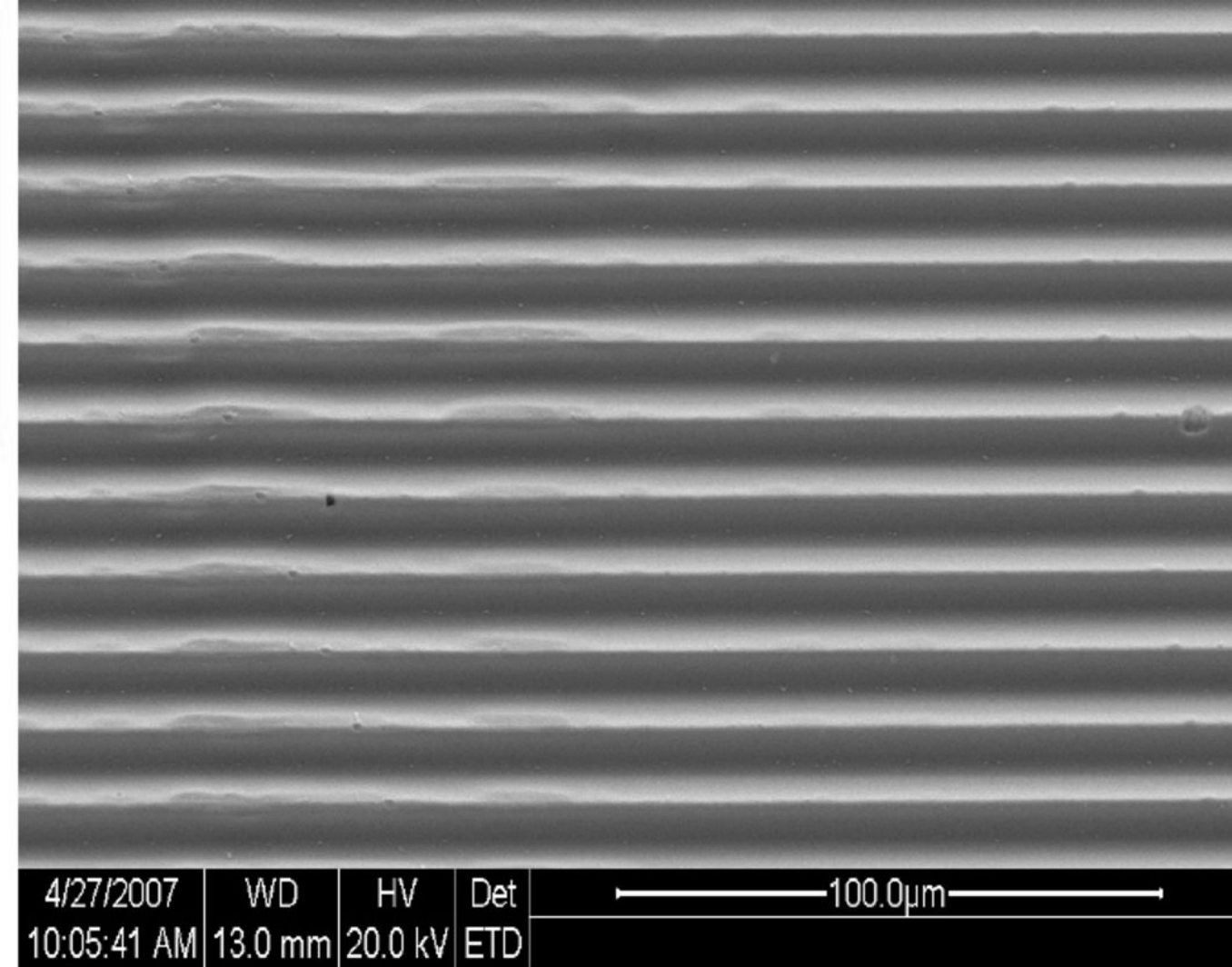
Figure 10. Relationship of the adhesive energy R and Young's modulus E

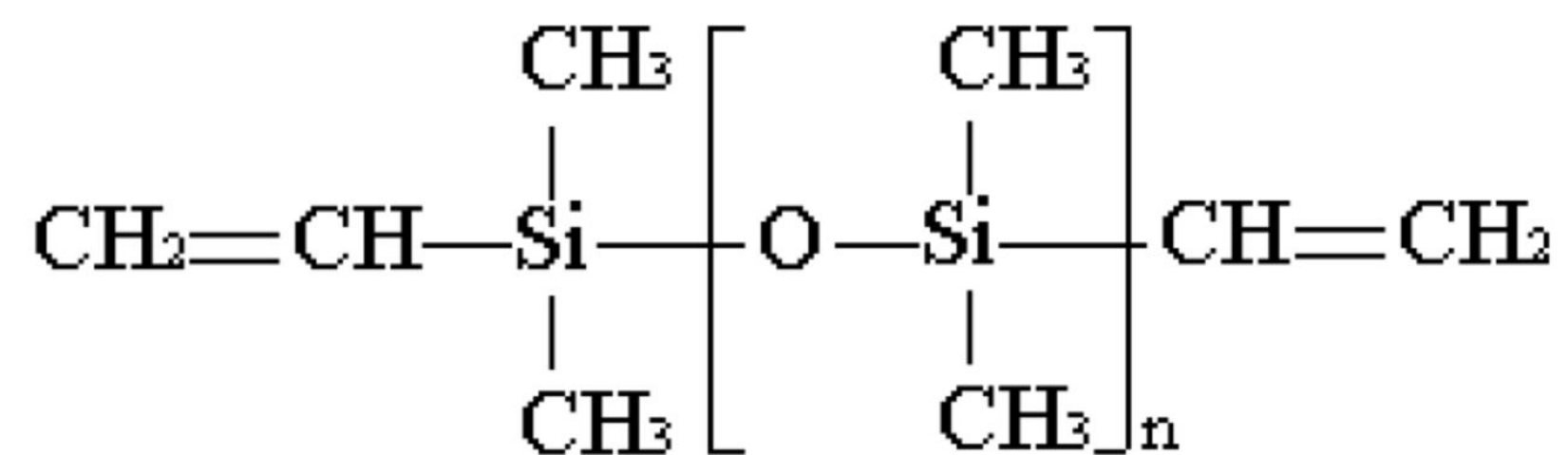
Figure 11. Dielectric permittivity test. ($\epsilon' = \epsilon'$ & $\epsilon'' = \epsilon''$)

Table legend

Table 1. Composition of the 18 samples and their properties

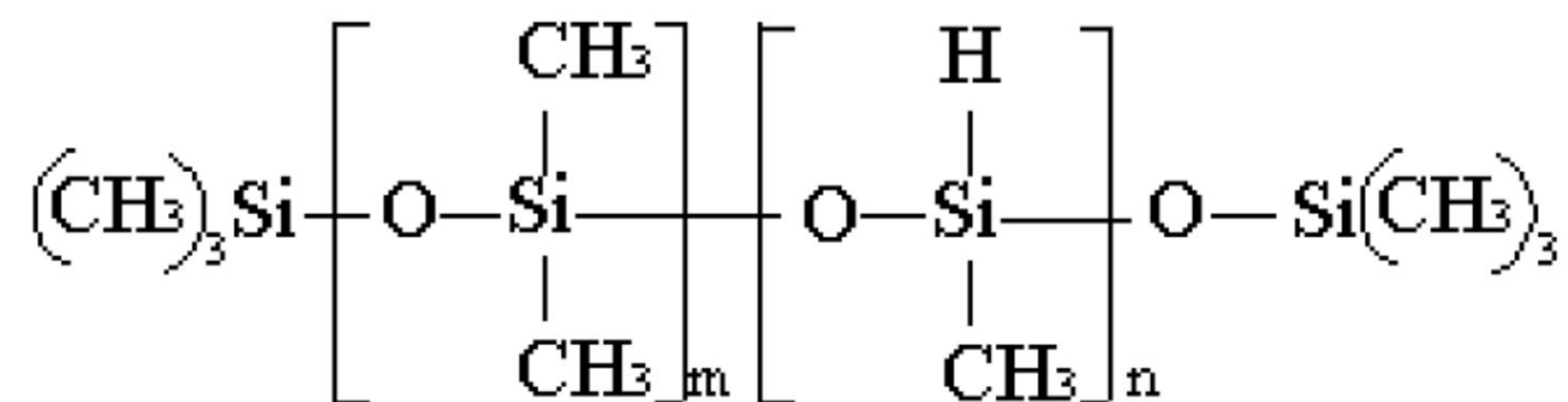






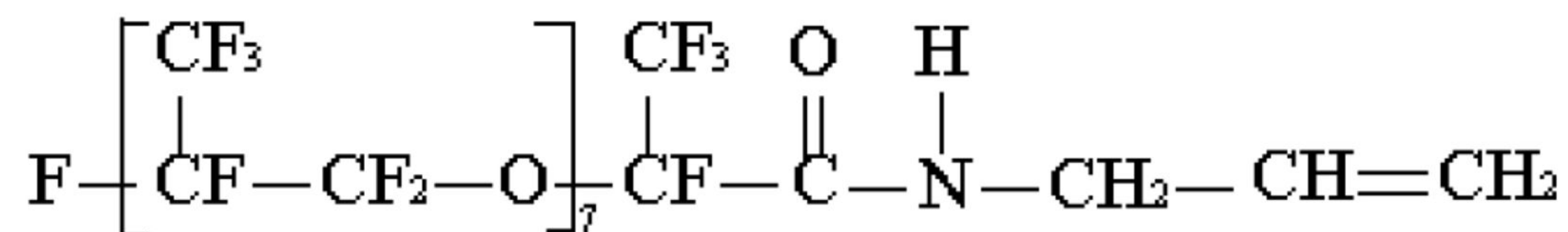
Polydimethyl Siloxane (PDMS)

+



Hydride crosslinker (HMS)

+



Perfluoroether allyl amide (PFE)

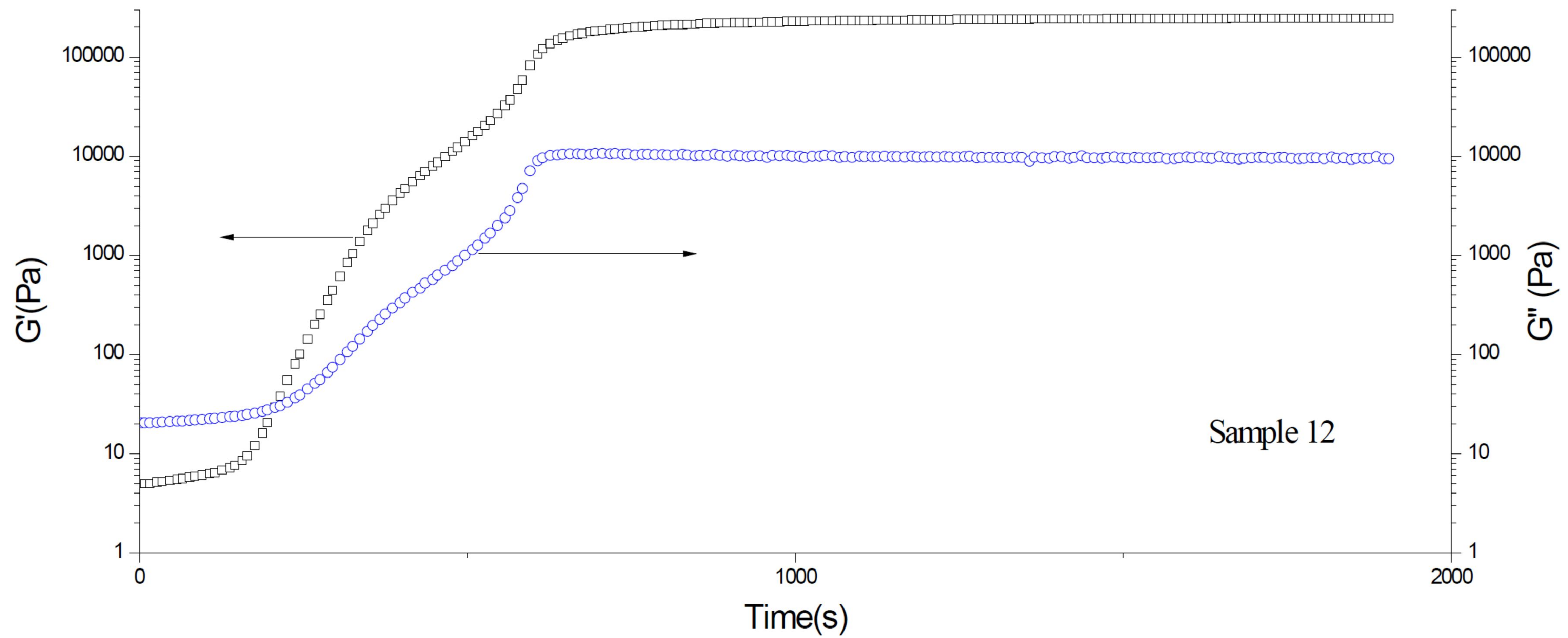
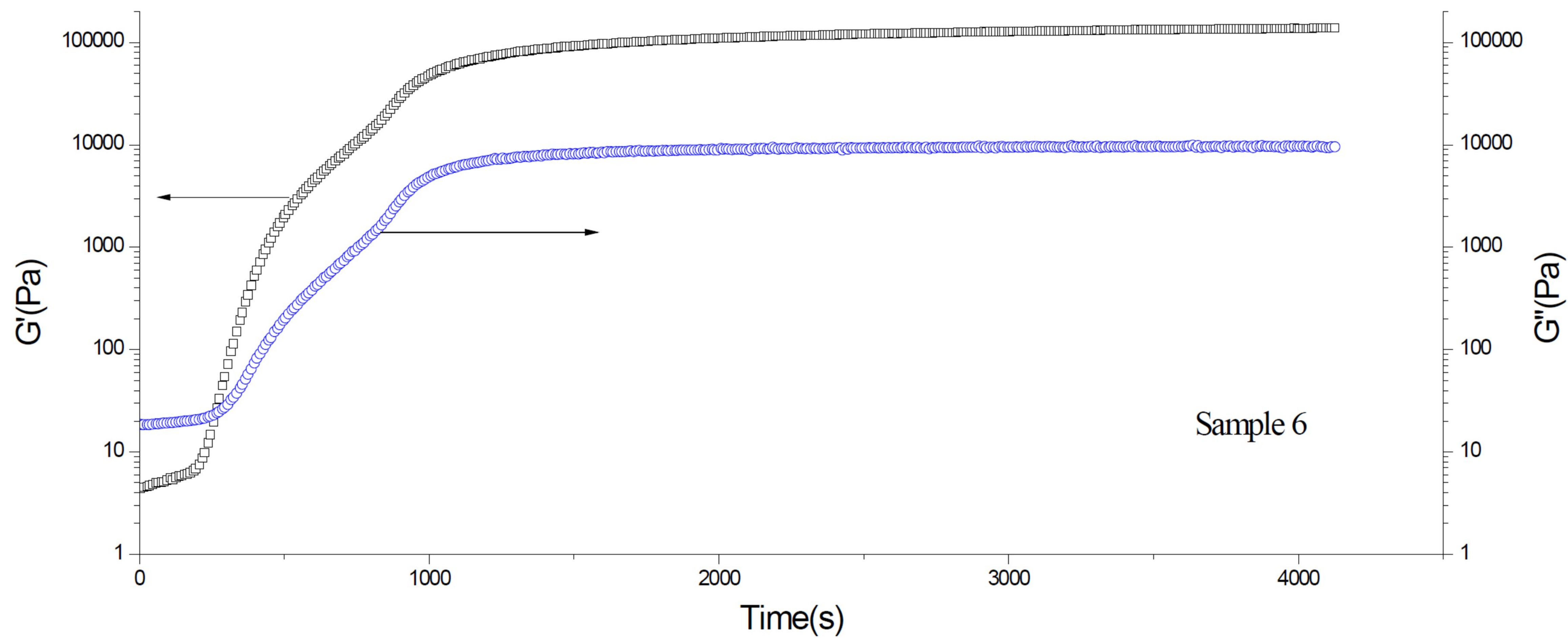
Pt catalyst

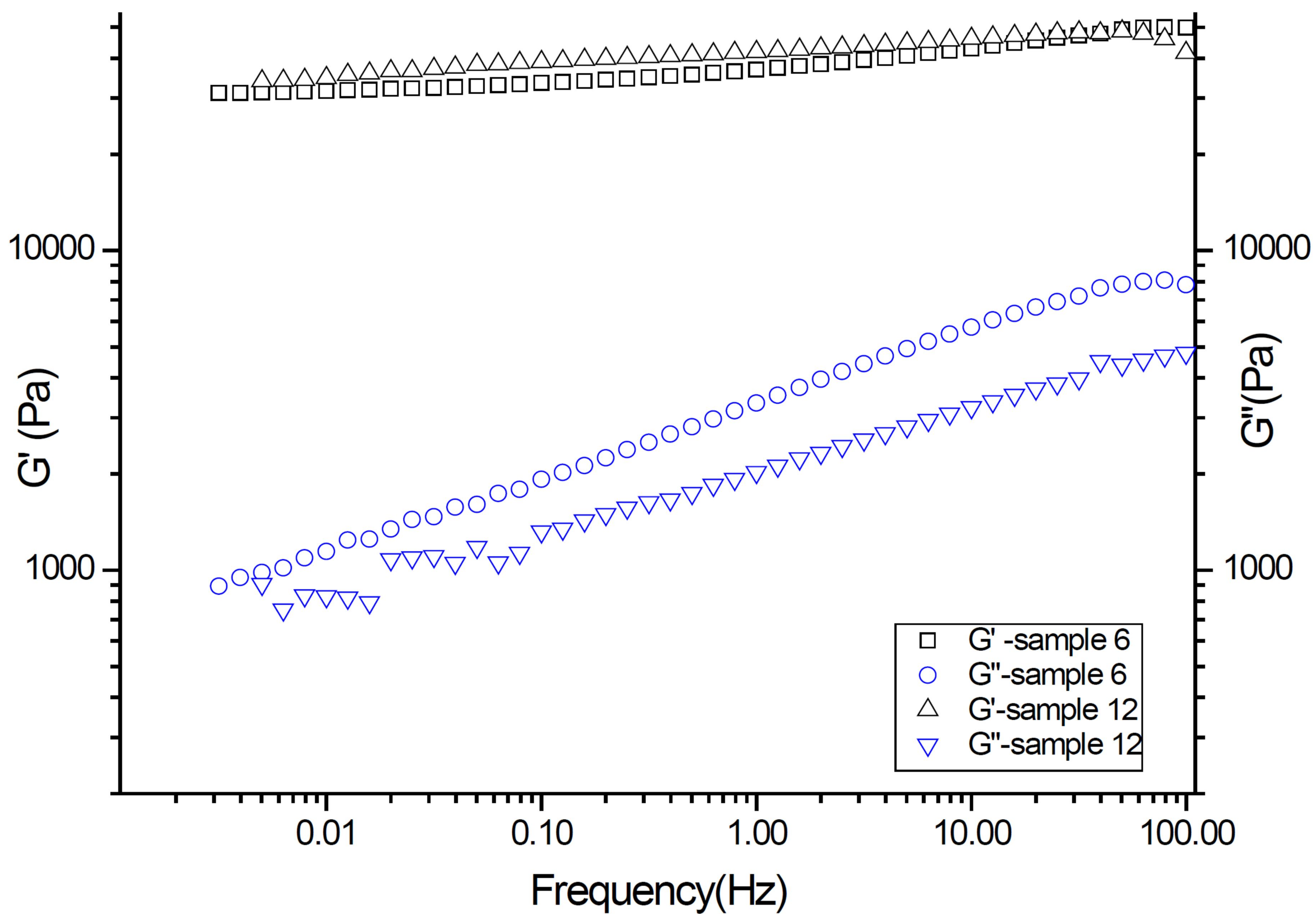


Perfluoroether allylamide(PFE)

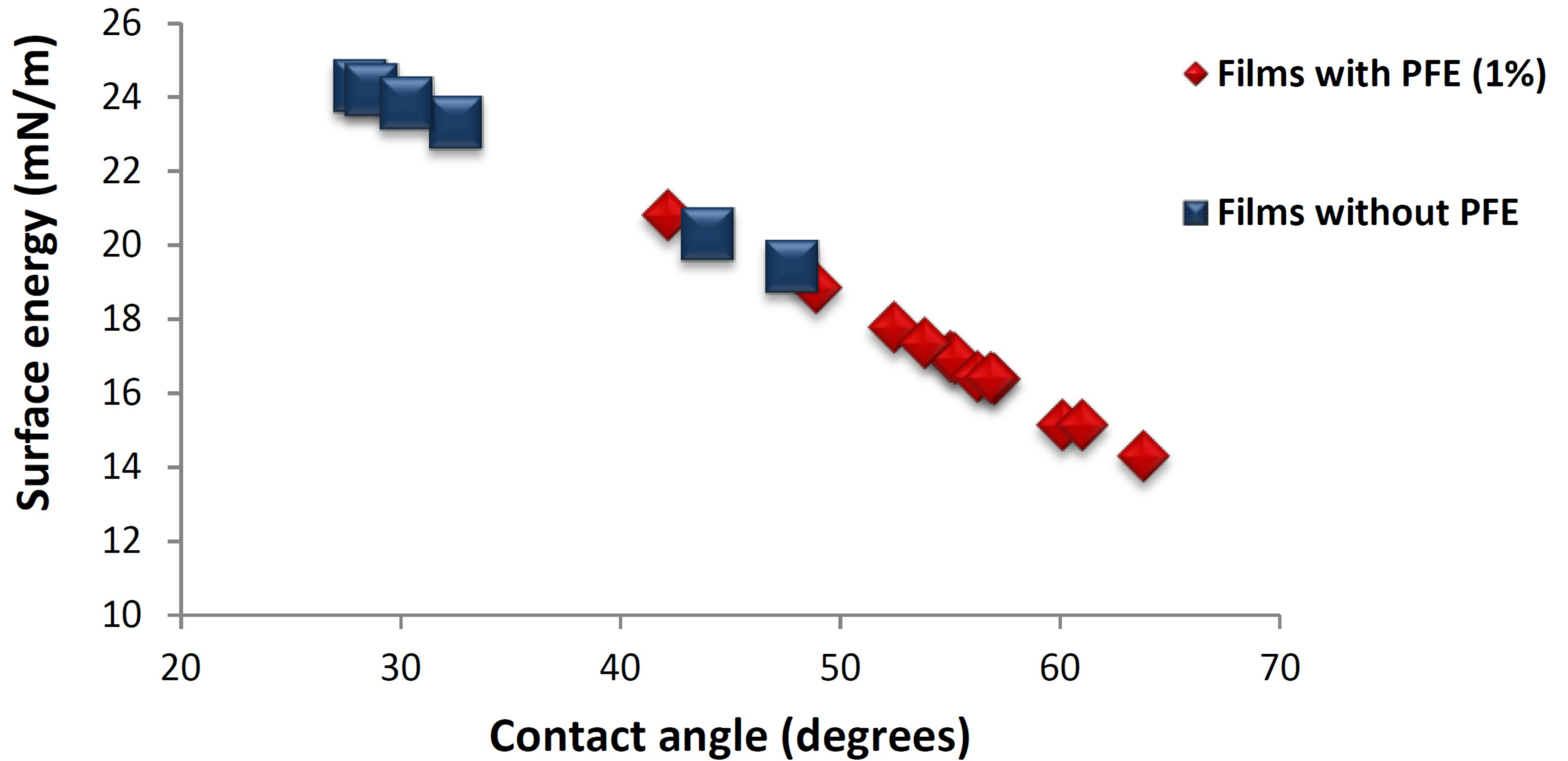


PDMS film(Network)

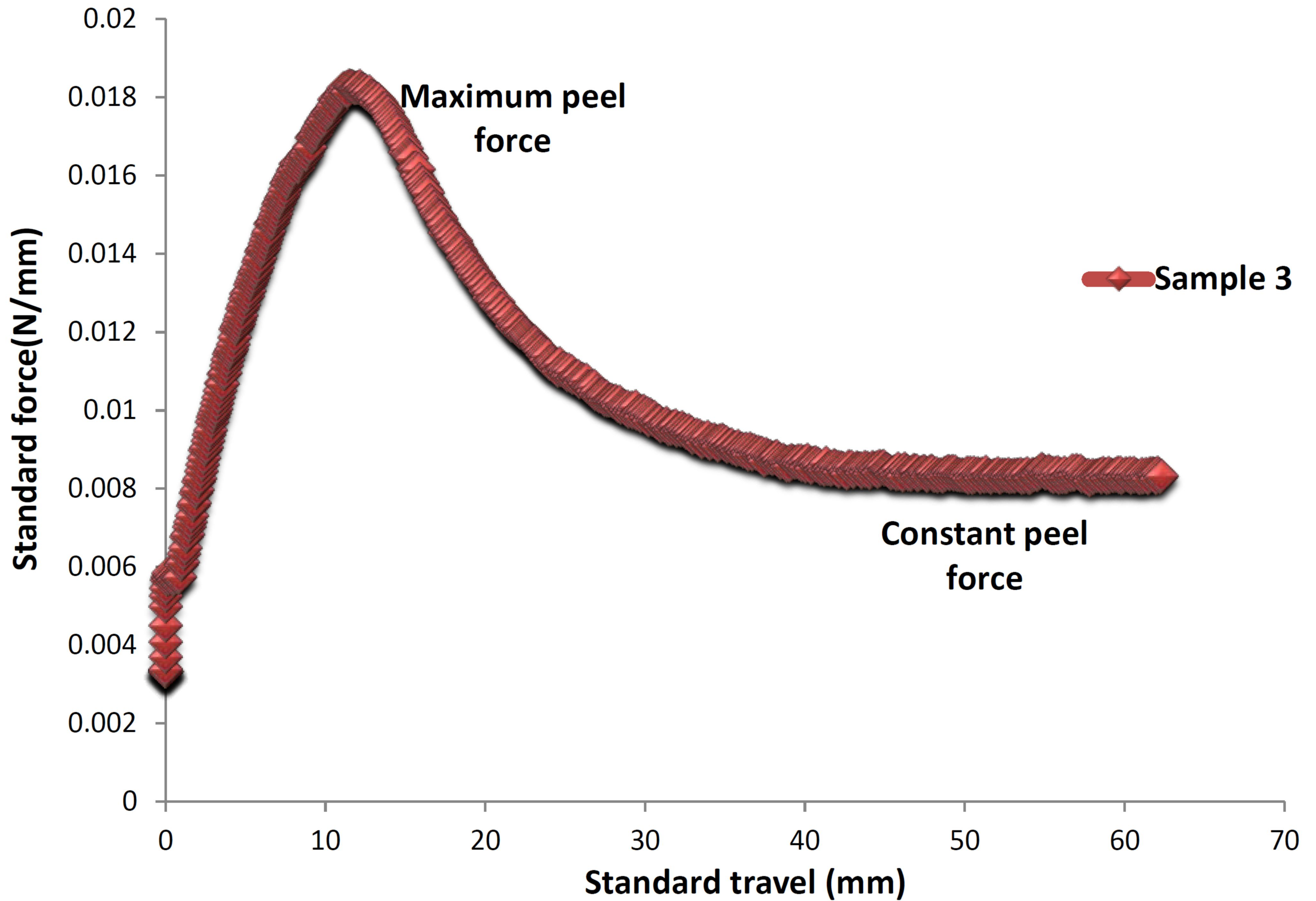




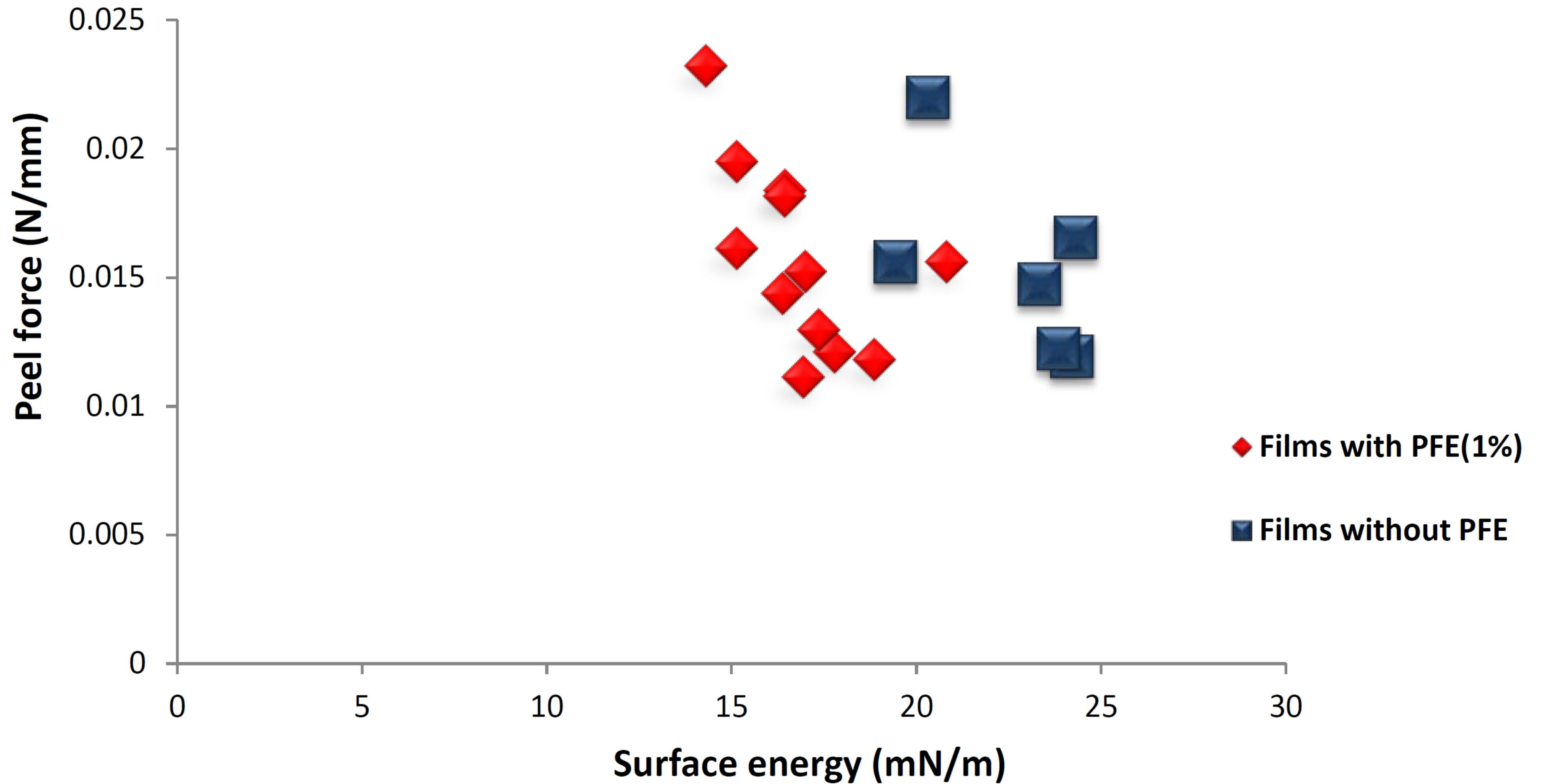
Surface energy



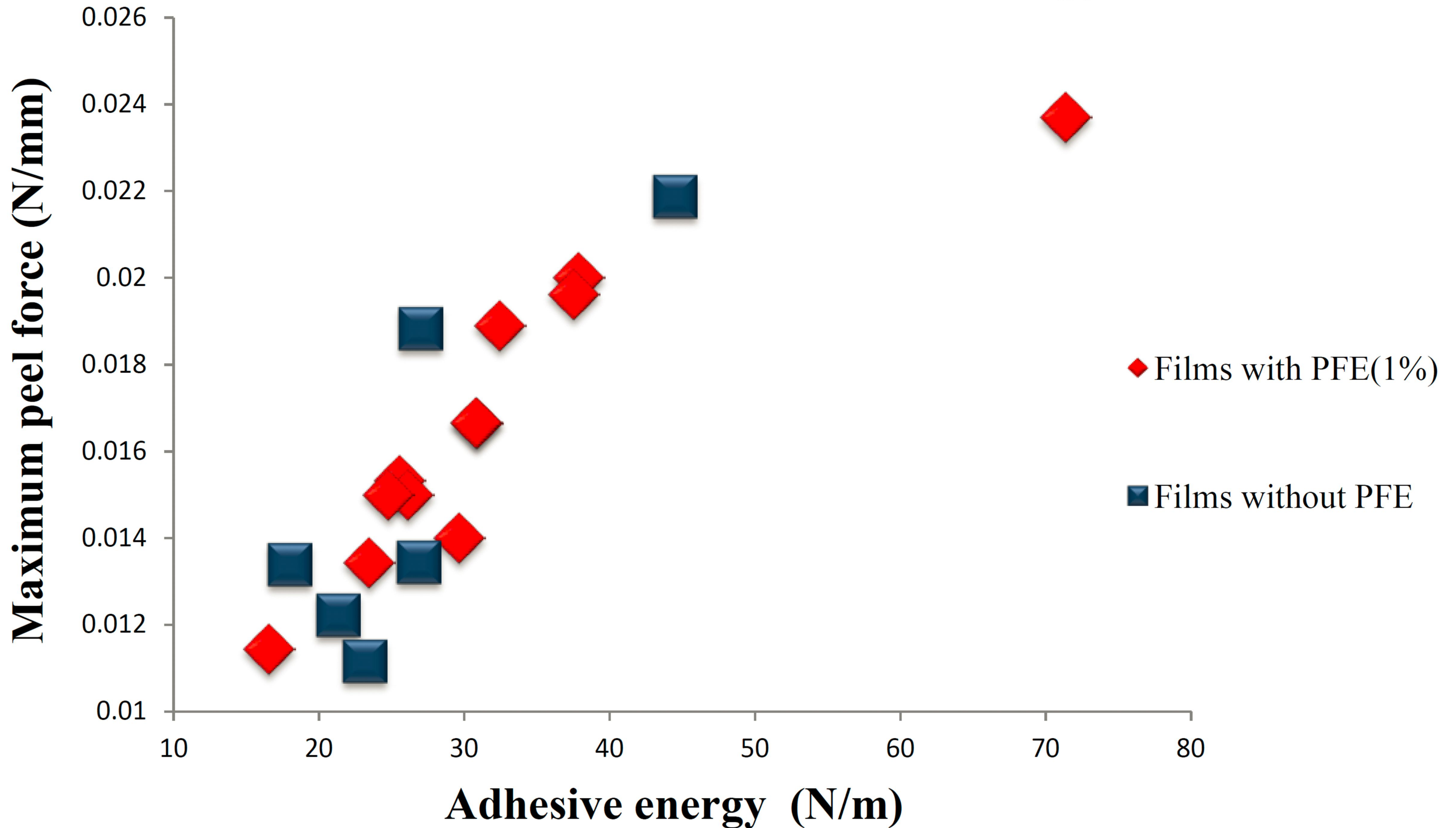
Peel force



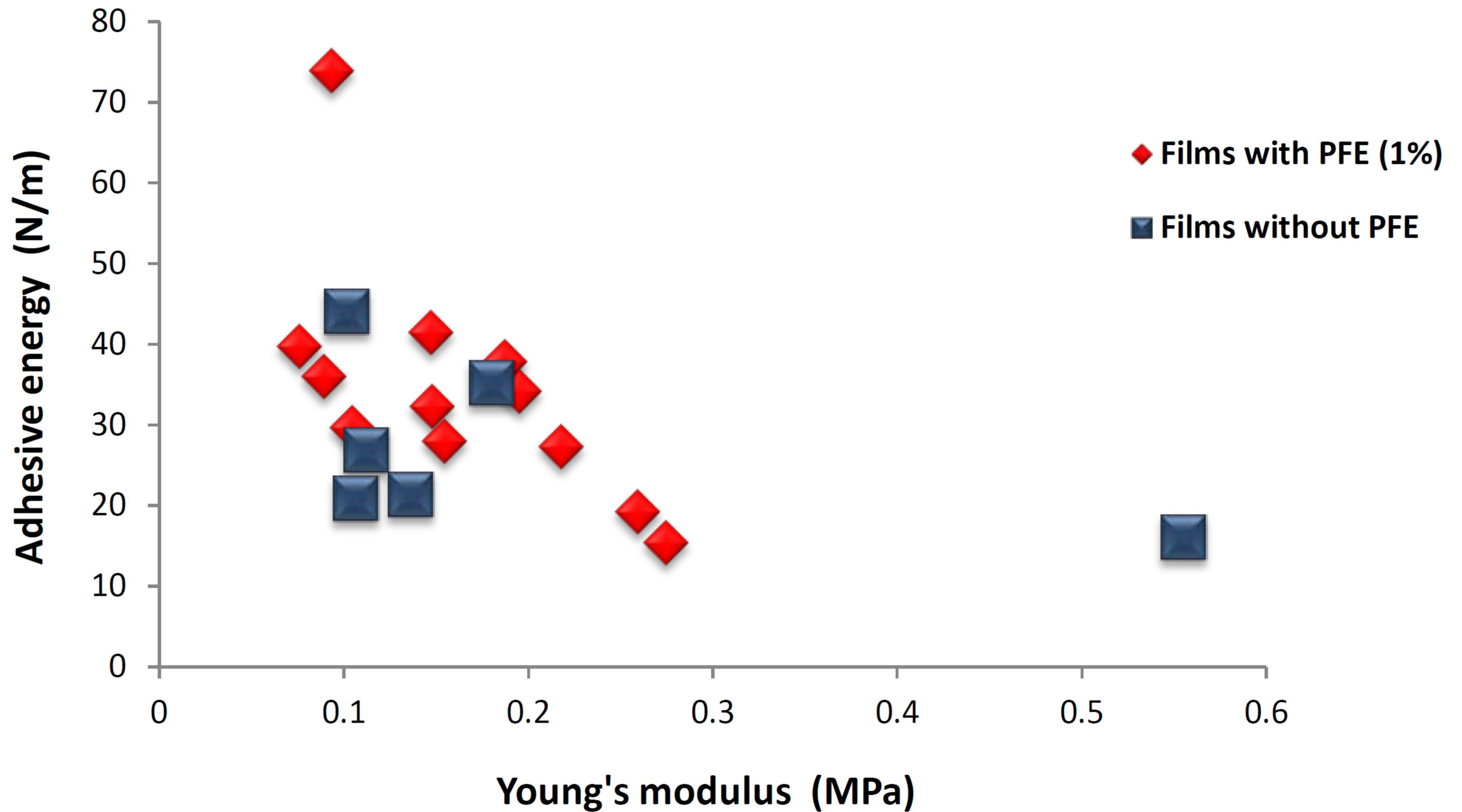
Surface energy & Peel force

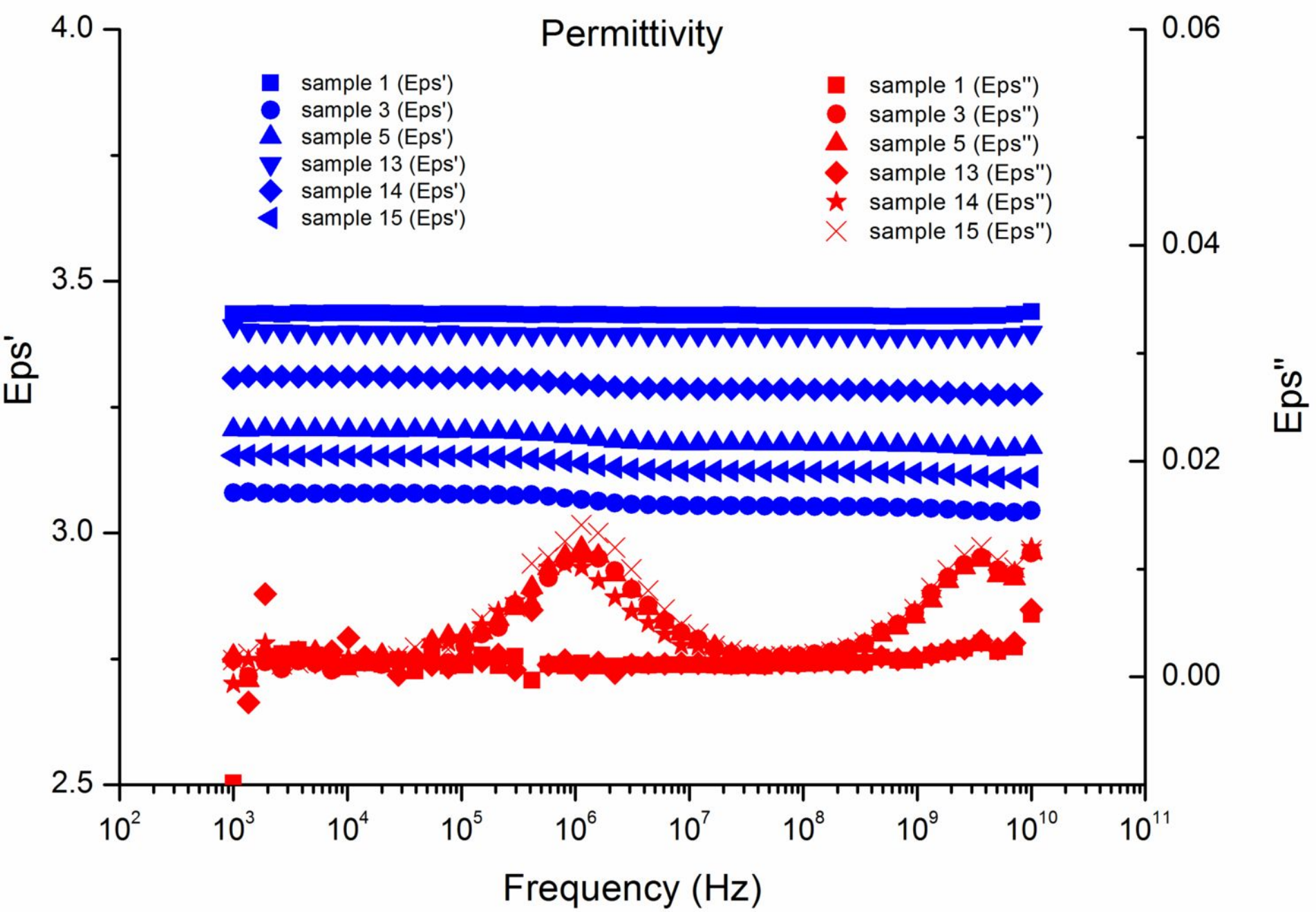


Peel force & Adhesive energy



Adhesive energy & Young's modulus





| Sample no. | Elastosil (A:B) | PF E (w/w %) | Inhibitor (w/w %) | Oil (w/w %) | Temperature (°C) | GP (minutes) | t_{97} (minutes) | $G'(\omega \rightarrow 0)$ (MPa) | $E=3G$ (MPa) | Contact angle with n-hexadecane | Surface energy (mN/m) | Max. peel force 'F' (N/m) | Average peel force (N/m) | Adhesive energy 'R' (N/m) |
|------------|-----------------|--------------|-------------------|-------------|------------------|--------------|--------------------|----------------------------------|--------------|---------------------------------|-----------------------|---------------------------|--------------------------|---------------------------|
| 1 | 9:1 | - | - | - | 23 | 65.8 | 780 | 0.19 | 0.57 | 32.5 | 23.3 | 0.015 | 0.007 | 16.1 |
| 2 | 9:1.1 | - | - | - | 23 | 53.9 | 317 | 0.06 | 0.18 | 28.2 | 24.3 | 0.017 | 0.009 | 27.0 |
| 3 | 9:1 | 1 | - | - | 23 | 50.5 | 406 | 0.06 | 0.18 | 55.0 | 17.0 | 0.018 | 0.008 | 34.2 |
| 4 | 9:1.1 | 1 | - | - | 23 | 54.7 | 789 | 0.05 | 0.15 | 60.1 | 15.1 | 0.016 | 0.009 | 32.3 |
| 5 | 9:1 | 1 | 0.8 | 15 | 80 | 5.2 | 52.2 | 0.05 | 0.15 | 57.0 | 16.4 | 0.014 | 0.009 | 28.0 |
| 6 | 9:1.1 | 1 | 0.8 | 15 | 80 | 4.4 | 67.8 | 0.03 | 0.09 | 63.8 | 14.3 | 0.023 | 0.014 | 73.9 |
| 7 | 9:1 | 1 | 0.8 | - | 80 | 4.4 | 19.8 | 0.06 | 0.18 | 61.0 | 15.1 | 0.019 | 0.013 | 37.8 |
| 8 | 9:1 | 1 | - | 15 | 23 | 77.3 | 1012 | 0.025 | 0.08 | 55.2 | 16.9 | 0.011 | 0.007 | 39.7 |
| 9 | 9:1.1 | 1 | 0.8 | - | 80 | 5.5 | 42.6 | 0.05 | 0.15 | 56.3 | 16.5 | 0.018 | 0.010 | 41.4 |
| 10 | 9:1.1 | 1 | - | 15 | 23 | 80.3 | 826 | 0.09 | 0.28 | 52.5 | 17.8 | 0.012 | 0.007 | 15.4 |
| 11 | 9:1 | - | 0.8 | 15 | 80 | 4.7 | 37.5 | 0.04 | 0.12 | 28.7 | 24.2 | 0.012 | 0.006 | 20.9 |
| 12 | 9:1.1 | - | 0.8 | 15 | 80 | 3.4 | 30.3 | 0.034 | 0.10 | 44.0 | 20.3 | 0.022 | 0.013 | 61.7 |
| 13 | 10:1 | - | - | - | 23 | 45.9 | 454 | 0.04 | 0.12 | 47.8 | 19.4 | 0.016 | 0.010 | 26.9 |
| 14 | 10:1 | 1 | - | - | 23 | 51.5 | 1246 | 0.09 | 0.27 | 42.2 | 20.8 | 0.016 | 0.008 | 19.2 |
| 15 | 10:1 | 1 | 0.8 | 15 | 80 | 7.9 | 87.5 | 0.04 | 0.12 | 53.9 | 17.4 | 0.013 | 0.009 | 29.6 |
| 16 | 10:1 | 1 | 0.8 | | 80 | 7.2 | 50.8 | 0.074 | 0.22 | 56.9 | 16.4 | 0.018 | 0.011 | 27.3 |
| 17 | 10:1 | 1 | - | 15 | 23 | 62 | 679 | 0.03 | 0.09 | 49.0 | 18.9 | 0.012 | 0.008 | 36.0 |
| 18 | 10:1 | - | 0.8 | 15 | 80 | 6.9 | 61 | 0.05 | 0.15 | 30.3 | 23.9 | 0.012 | 0.009 | 21.4 |

Factors affecting surface and release properties of thin Polydimethylsiloxane films

PDMS films were doped with 1% perfluoroether to lower the surface energy. Though the surface energy was lowered, the peel force did not decrease. It was found that peel force was linearly related to adhesive energy of films, and adhesive energy was inversely related to Young's modulus. Films with low Young's moduli evened out against surfaces easily and made good contact, which increased the adhesive forces, making the release hard. Comparatively, films with higher Young's moduli had low peel force.

